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Recent advances in laser and optical technologies have now enabled the current generation of high intensity, ultrashort-pulse lasers to achieve focal intensities of 10^{20}-10^{21}W/cm^2 in pulse durations of 100-500fs. These ultraintense laser pulses are capable of producing highly relativistic plasma states with densities, temperatures, and pressures rivaling those found in the interiors of stars and nuclear weapons. Developing the techniques to recreate such extreme states of matter in the laboratory, under controlled and well-characterized conditions, is a prerequisite for obtaining the experimental data necessary to validate and benchmark theoretical models for atomic kinetics, equations of state, and opacities.

Utilizing the ultraintense 100TW JanUSP laser at LLNL we have explored the possibility of ion shock heating small micron-sized plasmas to extremely high energy densities approaching 1GJ/g on timescales of a few hundred femtoseconds. The JanUSP laser delivers 10 Joules of energy in a 100fs pulse in a near diffraction-limited beam, producing intensities on target of up to 10^{21}W/cm^2. The electric field of the laser at this intensity ionizes and accelerates electrons to relativistic MeV energies. The sudden ejection of electrons from the focal region produces tremendous electrostatic forces which in turn accelerate heavier ions to MeV energies. The predicted ion flux of 1 MJ/cm^2 is sufficient to achieve thermal equilibrium conditions at high temperature in solid density targets.

Our initial experiments were carried out at the available laser contrast of 10^7 (i.e. the contrast of the amplified spontaneous emission (ASE), and of the pre-pules produced in the regenerative amplifier). At such a pre-pulse level one expects a significant amount of pre-plasma and thus high absorption into hot electrons. Thus, our first measurements were of the high energy (multi-MeV) electron and associated gamma production. We used the nuclear photoactivation of Au-197 samples to measure the gamma production above 12MeV—corresponding to the threshold for the Au-197(γ,n) reaction. Since the predominant mechanism for gamma production is through the bremsstrahlung emission of energetic electrons as they pass through the solid target we were able to infer a conversion yield of several percent of the incident laser energy into electrons with energies >12MeV. This result is consistent with the interaction of the main pulse with a large pre-formed plasma.

The contrast of the laser was improved to the 10^{-10} level by the insertion of two additional pockel cells to reduce the pre-pulse intensities, and by the implementation of a pulse clean up technique based on adding an additional pre-amplifier and saturable absorber which resulted in a reduction in the ASE level by a factor of approximately 1000.

In FY00/01 we performed a series of experiments to investigate the mechanisms for ion generation and acceleration in thin foil targets irradiated at incident laser intensities above 10^{20} W/cm^2, and with the laser contrast at 10^{-10}. Full details of this work can be found in the two accompanying papers: *Energy spectrum and angular distribution of multi-MeV protons produced from ultraintense laser interactions,* UCRL-JC-143112, P.K. Patel *et al.,* and *Enhancement of proton acceleration by hot electron re-circulation in thin foils irradiated by ultra-intense laser pulses,* A.J. Mackinnon *et al.* UCRL-JC-145540.

To summarize the accompanying papers, we observed a highly directional ion beam emitted in the rear direction normal to the target surface. An ion time-of-flight magnetic spectrometer showed this beam to comprise both heavy target ions and protons. To obtain a more complete picture of the ion emission a range of detectors were developed and fielded including radiachromic films (measuring ion, electron, and x-ray dose), nuclear activation detectors (high energy protons), and single particle nuclear track detectors (protons and heavy ions). Significantly we found that a large fraction of the incident laser energy (greater than 1%) is coupled to highly energetic protons forming a well-collimated beam. The proton spectrum can be fit by an exponential distribution containing 10^{11} particles with a mean energy of 3 MeV and a high energy cutoff of 25 MeV. However, these particles appear to originate not from the interaction region at the front of the target but rather from a thin adsorption layer on the rear surface.

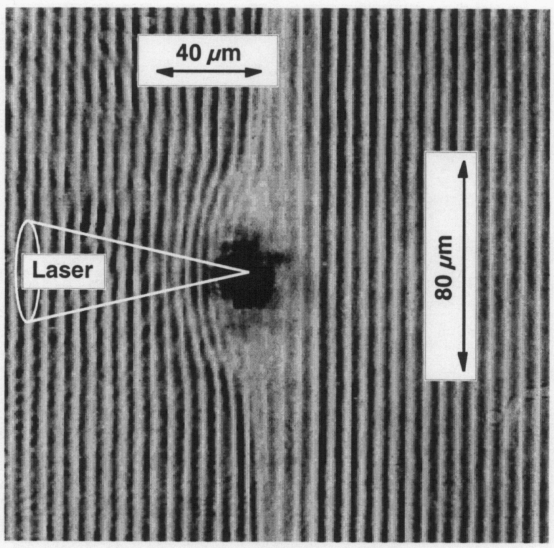

Fig. 1. Interferogram of a 10μm Al foil irradiated with 11.8J laser energy, taken 50ps before the main pulse.

Figure 1 shows an interferogram of a foil taken with a frequency-doubled probe beam timed to arrive approximately 50ps before the main pulse. It shows that even with the improved laser contrast the laser intensity is still sufficiently high to create a small pre-formed plasma. This level of pre-plasma will preclude any possibility of substantial forward ion acceleration at the front surface. Using these experimental conditions particle-in-cell (PIC) simulations were carried out of the laser interaction with the foil. These simulations show that the first hot electrons generated by the laser propagate through the target and escape into vacuum. As more electrons escape the target becomes positively charged and an electrostatic field is set up at the rear surface. This field rapidly increases in magnitude on a time-scale of just a few femtoseconds until eventually it stops and repels further electrons back into the target. Simultaneously it drags the heavier positively charged ions from the rear surface, accelerating them along the direction of the electric field normal to the surface. Since protons are the lightest element in the target they attain the highest velocity and thus form the leading edge of the ion front. Furthermore, they effectively shield the heavier ions in the target behind the front which hence see a much smaller accelerating field.

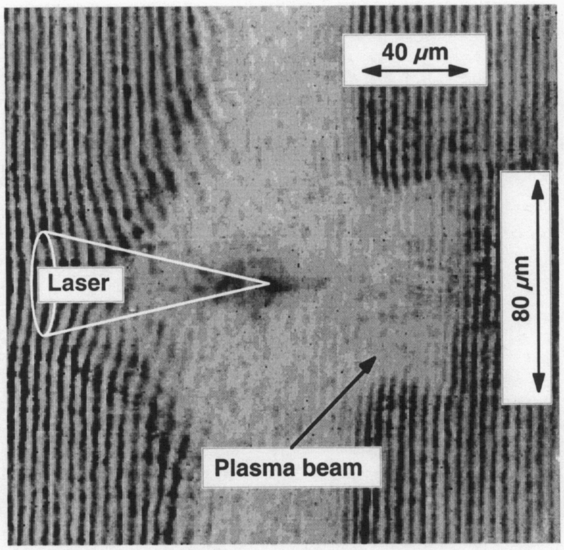

Fig. 2. Interferogram of a 10μm Al foil irradiated with 8.6J laser energy, taken 150ps after the main pulse.

This theory supports the experimental evidence of such high conversion efficiencies of the laser energy into protons. Figure 2 shows an interferogram taken 150ps after the main pulse. It reveals a highly collimated beam-like expansion at the rear surface. The unexpected presence of this rear surface ion beam presents a significant problem in distinguishing the point of origin of forward accelerated ions. It appears likely that both components—ponderamotively accelerated ions from the front surface, and electrostatically accelerated ions from the rear surface—are present in the forward directed ion beam. Our current experimental campaign includes investigating techniques to remove the presence of light ion contaminants on the foils in order to more efficiently accelerate heavier ions, and to frequency-double the 800nm JanUSP light to reach the necessary intensity contrast for the ponderamotive acceleration mechanism to dominate.

This work has been submitted in two papers to Physical Review Letters. The new electrostatic acceleration mechanism has sparked considerable interest in the scientific community and has initiated a host of projects at LLNL and other ultrashort-pulse laser facilities worldwide. Our findings have specifically resulted in the formation and funding of two new LDRD projects in FY01 and FY02—one to assess the feasibility of developing proton radiography as a diagnostic of transient high-magnitude electric and magnetic fields in laser-produced plasmas, and another to develop a capability for employing the proton beam to isochorically heat large-volume material samples to states in the warm dense plasma regime.